Probing the top quark interaction at Colliders

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outline

- Forward-backward asymmetry of the top pair production at TEVATRON
- Triple top in SM and BSM
- Azimuthal angular correlation of the top events at LHC
- Tops in LC
- Higgs coupling to top

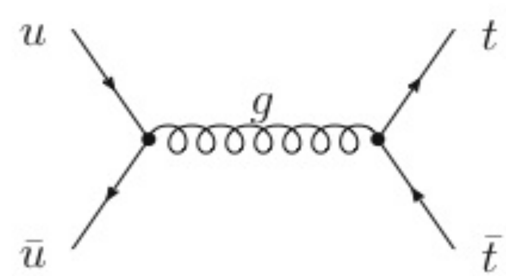
Measurements of $A_{t\,FB}$

$$A_{fb} \equiv \frac{N_t(\cos\theta > 0) - N_t(\cos\theta < 0)}{N_t(\cos\theta > 0) + N_t(\cos\theta < 0)}$$

$0.20 \pm 0.11_{\text{stat.}} \pm 0.047_{\text{syst.}}$	(0.695/fb CDF Schwarz Thesis)
$0.19 \pm 0.09_{\text{stat.}} \pm 0.02_{\text{syst.}}$	(0.9/fb D0 0712.0851)
$0.17 \pm 0.07_{\text{stat.}} \pm 0.04_{\text{syst.}}$	(1.9/fb CDF 0806.2472)
$0.193 \pm 0.065_{\text{stat.}} \pm 0.024_{\text{syst.}}$	(3.2/fb CDF note 9724)

Large at both CDF and D0

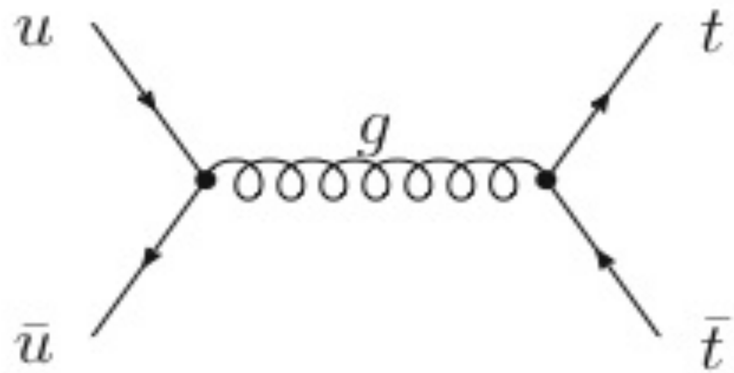
QCD gives ~ 0.05 only



Recent CDF analysis show mass dependent forward-backward top-pair asymmetry.

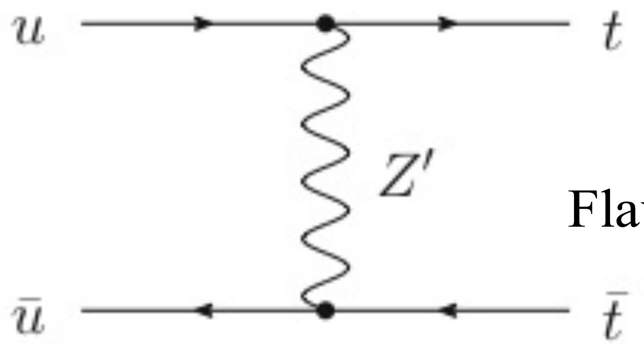
$$A^{t\bar{t}}(M_{t\bar{t},i}) = \frac{N(\Delta y > 0, M_{t\bar{t},i}) - N(\Delta y < 0, M_{t\bar{t},i})}{N(\Delta y > 0, M_{t\bar{t},i}) + N(\Delta y < 0, M_{t\bar{t},i})},$$

$$A_{FB} = 0.475 \pm 0.114 \text{ for } M_{t\bar{t}} > 450 \text{ GeV}$$



Next-to-Leading Order (NLO)

$$0.088 \pm 0.013$$



Jung, Murayama, Pierce, Wells

Flavor changing, same sign top pair at LHC

K. Cheung, WYK, and T.C. Yuan looked at the charged W' instead of the neutral Z', 0908.2589.

$$\mathcal{L} = -g' \, W'^{+}_{\mu} \, \bar{t}\gamma^{\mu} \left(g_L P_L + g_R P_R \right) d \; + \; \text{h.c.}$$

Generate large A_{FB} by 1/t exchange and by helicity matching.

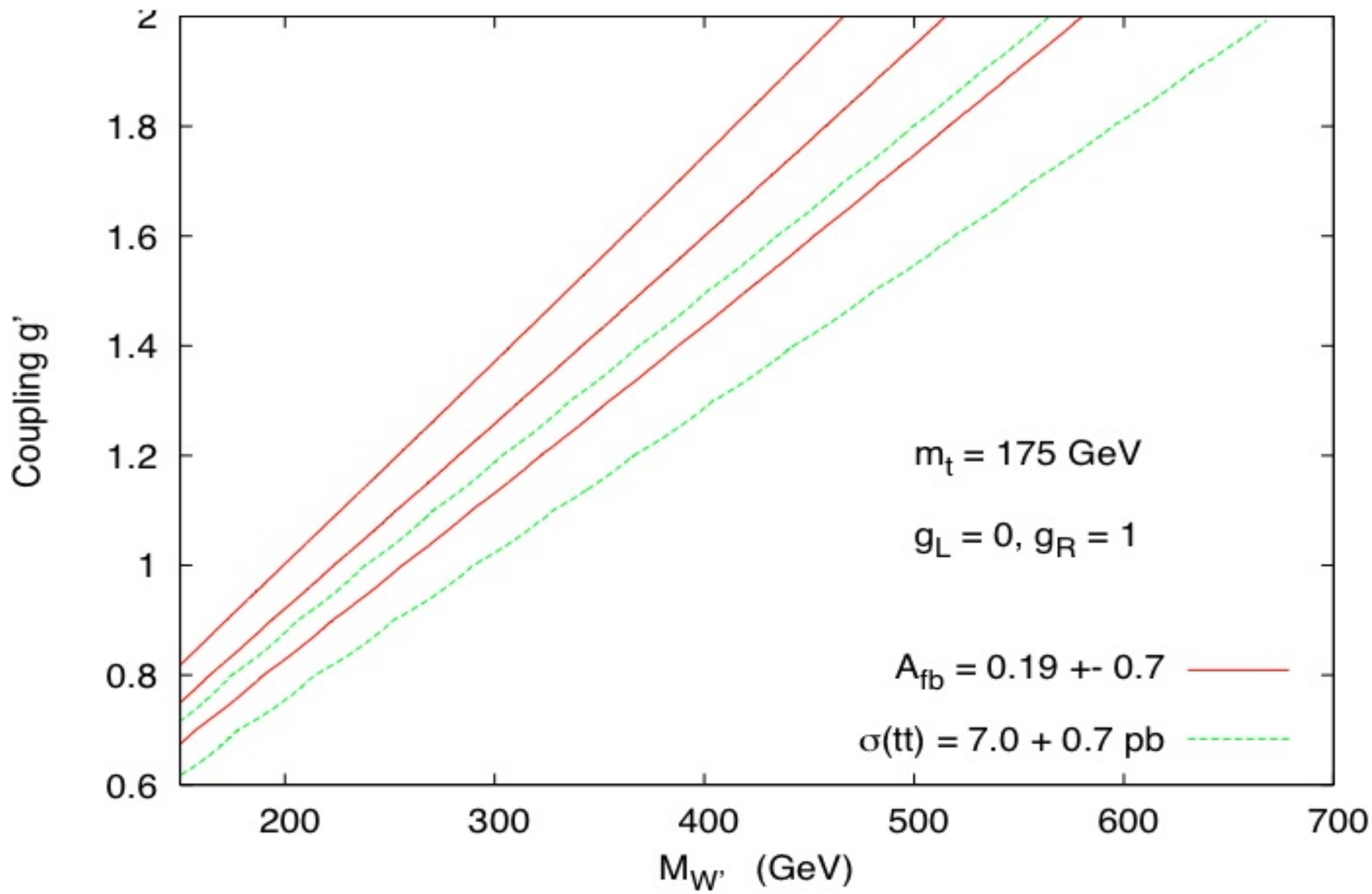
Simple formulas $\sum |\mathcal{M}|^2$ (for V and S)

$$\frac{9g'^4}{t_{W'}^2}\left[4\left((g_L^4+g_R^4)u_t^2+2g_L^2g_R^2\hat{s}(\hat{s}-2m_t^2)\right)+\frac{m_t^4}{m_{W'}^4}(g_L^2+g_R^2)^2(t_t^2+4m_{W'}^2\hat{s})\right]$$

$$\frac{16g_s^4}{\hat{s}^2}\left(u_t^2+t_t^2+2\hat{s}m_t^2\right)+\frac{16g'^2g_s^2}{\hat{s}\,t_{W'}}(g_L^2+g_R^2)\left[2u_t^2+2\hat{s}m_t^2+\frac{m_t^2}{m_{W'}^2}(t_t^2+\hat{s}m_t^2)\right]$$

$$\hat{s}=(p_1+p_2)^2,\ t=(p_1-k_1)^2,\ u=(p_1-k_2)^2 \qquad t_{W'}=t-m_{W'}^2$$

$$u_t=u-m_t^2=-\tfrac{1}{2}\hat{s}(1+\beta\cos\theta)\,,\quad t_t=t-m_t^2=-\tfrac{1}{2}\hat{s}(1-\beta\cos\theta)$$



The contour of the asymmetry in $t\bar{t}$ production in the plane of $(M_{W'},\ g')$.

$A_{fb} = 0.12,\ 0.19$ and 0.26. The chiral couplings for $W' - d - t$ are $g_L = 0,\ g_R = 1$.

W' and Z' Models

Asymmetric Left-Right Model

V. Barger, W.-Y. Keung, C.-T. Yu
[arXiv:1002.1048], [arXiv:1102.0279]

Right-Handed W'

K. Cheung, W.-Y. Keung, T.-C. Yuan
[arXiv:0908.2589],
K. Cheung, T.-C. Yuan
[arXiv:1445]

W'-d-t

see also:
[arXiv:1101.5392] J. Shelton, K. Zurek

Non-universal Z'

S. Jung, H. Murayama, A. Pierce, J. Wells
[arXiv:0907.4112],
S. Jung, A. Pierce, J. Wells
[arXiv:1104.3139], [arXiv:1104.4835]

Z'-u-t

Asymmetric Left-Right Model

V. Barger, W.-Y. Keung, C.-T. Yu
[arXiv:1002.1048], [arXiv:1102.0279]

We begin with the gauge group $\boxed{U'(1) \times SU'(2) \times SU(2)}$

$$
\begin{aligned}
U'(1) &\to g_1', B' \\
SU'(2) &\to g_2', W' \\
SU(2) &\to g_2, W
\end{aligned}
$$

which is broken sequentially down to the SM

Asymmetric Left-Right Model

$$U'(1) \times SU'(2) \times SU(2)$$

$$\Big\Downarrow \quad \frac{Y}{2} = T_3' + \frac{Y'}{2}$$

$$U_Y(1) \times SU(2)$$

$$\Big\Downarrow \quad Q = T_3 + \frac{Y}{2}$$

$$U_{EM}(1)$$

Sequential approximation preserves the SM interactions

An investigation of Z-Z' mixing in such a model can be found in:
[arXiv:1101.5392] J. Shelton, K. Zurek
[arXiv:1104.0083] J. Shu, K. Wang, G. Zhu

Asymmetric Left-Right Model

First, we rotate into B, Z' basis and have:

$$g_1' \frac{Y'}{2} B' + g_2' T_3' W_3' = \left(\frac{g_1' g_2'}{\sqrt{{g_1'}^2 + g_2'^2}} \right) \frac{Y}{2} B + \sqrt{g_1'^2 + g_2'^2} \left(T_3' - \frac{g_1'^2 \frac{Y}{2}}{g_1'^2 + g_2'^2} \right) Z'$$

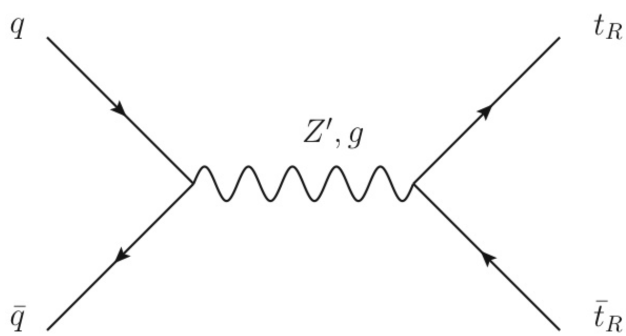
Subsequently, we perform the usual SM rotation from B, W_3 to A, Z

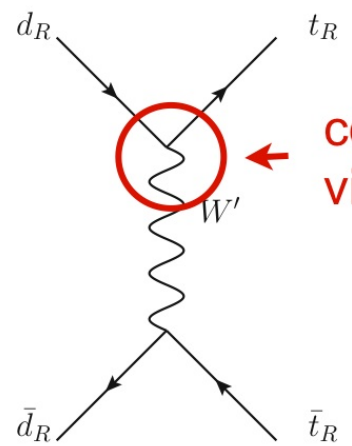
$$U_Y(1) \;\; g_1 = g_1' g_2' / g' = e / c_W$$

$$SU(2) \;\; g_2 = e / s_W$$

After symmetry breaking, we have new Z' and $W'^{\pm}$ bosons

New Interactions:





contributes to parity violation

$$L \supset g' \left(\bar{t}, \bar{d}\right)_R \gamma^\mu T_3' Z_\mu' \begin{pmatrix} t \\ d \end{pmatrix}_R$$

$$L \supset (g_2'/\sqrt{2})\bar{t}_R \gamma^\mu d_R W_\mu'$$

Asymmetric Left-Right Model

- New data allows for a higher W' mass since A_{FB} anomaly is at high $M_{t\bar{t}}$
- assume a Higgs mechanism due to a complex triplet Higgs ϕ'

$$\langle \phi' \rangle = (0, 0, v'/\sqrt{2})^T$$

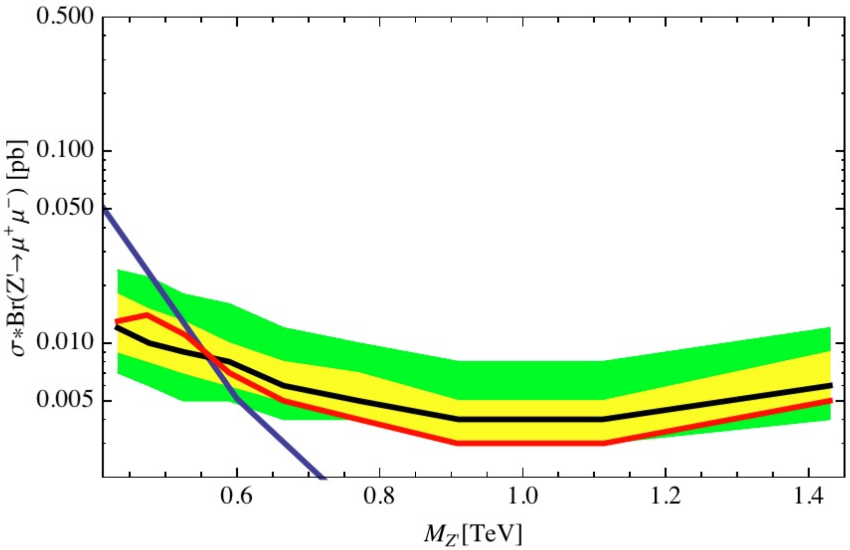
$$M_{Z'} = g'v'$$

$$M_{W'} = \frac{1}{\sqrt{2}} g_2' v'$$

$$\Rightarrow \quad \boxed{\frac{M_{W'}}{M_{Z'}} = \frac{g_2'}{\sqrt{2}g'} \simeq \frac{1}{\sqrt{2}}}$$

Asymmetric Left-Right Model

Z' coupling has the form: $$g' T'_3 - \frac{g_1'^2}{g'}(Q_q - T_{3,q}^{SM})$$



Dimuon search at CDF requires $M_{Z'}$>500 GeV for g'_2=3

$$M_{W'} = 700 \text{ GeV}$$
$$M_{Z'} = 1 \text{ TeV}$$
$$g'_2 = 3$$

Asymmetric Left-Right Model

$$M_{W'} = 700 \text{ GeV}$$
$$M_{Z'} = 1 \text{ TeV}$$
$$g'_2 = 3$$

$$\Gamma_{W'} = 114 \text{ GeV}$$
$$\Gamma_{Z'} = 168 \text{ GeV}$$
$$\mathcal{BR}(Z' \to d\bar{d}) = 0.5$$
$$\mathcal{BR}(Z' \to t\bar{t}) = 0.5$$
$$\mathcal{BR}(Z' \to l\bar{l}) = 6.0 \times 10^{-4}$$

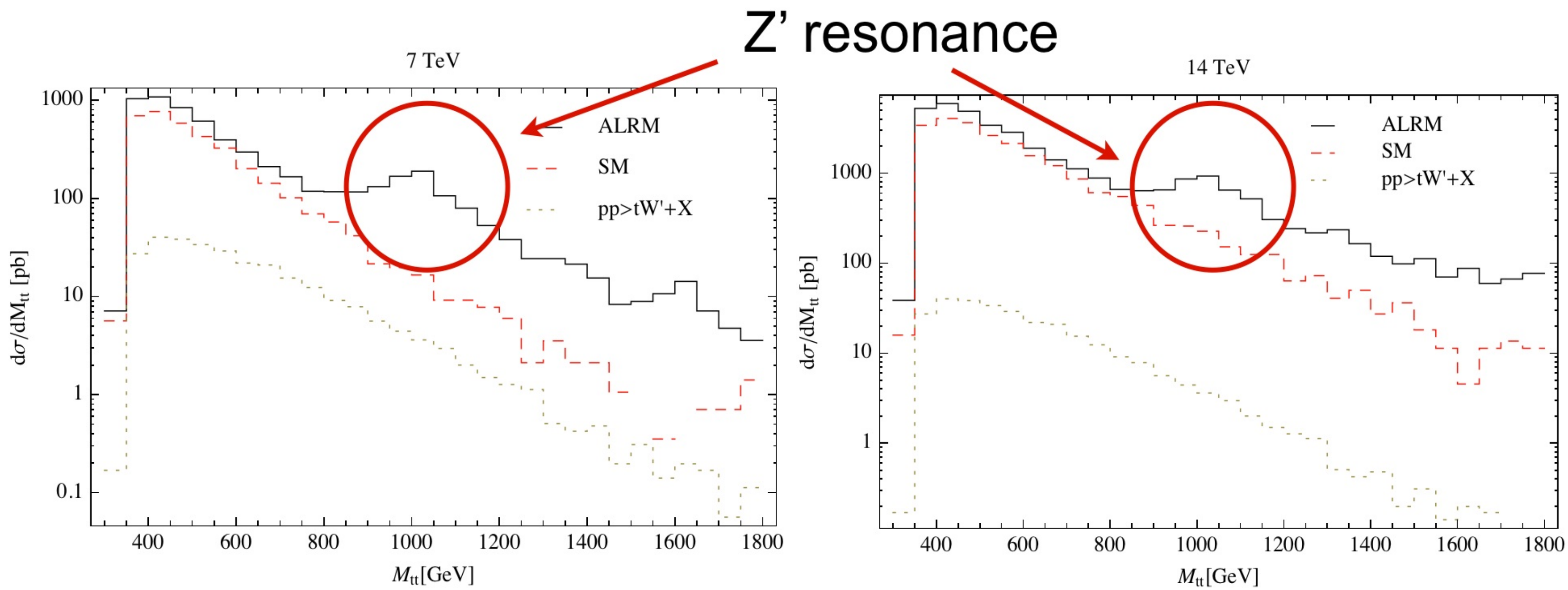
The small leptonic width + broad total width will make Z' detection difficult in Drell-Yan lepton channel.

Asymmetric Left-Right Model

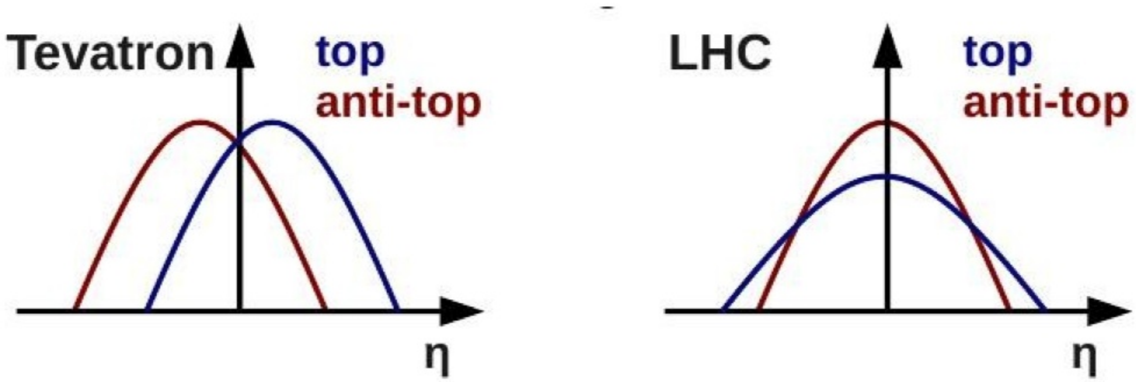
Results:

g_2'	$M_{W'}$ [GeV]	$\sigma(t\bar{t})$ [pb]	A_{FB}	A_{FB} $M_{t\bar{t}} < 450$ GeV	A_{FB} $450 < M_{t\bar{t}} < 800$ GeV	A_{FB} $\|\Delta y\| < 1$	A_{FB} $\|\Delta y\| > 1$
3.0	700	8.45	0.06	-0.01	0.136	0.03	0.14
3.5	700	9.05	0.11	0.01	0.22	0.06	0.26
3.5	650	9.8	0.16	0.03	0.26	0.06	0.36
3.0	550	10.4	0.22	0.04	0.33	0.09	0.42
2.5	500	10.5	0.19	0.003	0.32	0.07	0.40
Data [4] [19]		7.70 ± 0.52	0.158 ± 0.074	-0.116 ± 0.153	0.475 ± 0.122	0.026 ± 0.118	0.611 ± 0.256
SM		$7.45^{+0.72}_{-0.63}$	0.058 ± 0.009	0.04 ± 0.006	0.088 ± 0.0013	0.039 ± 0.006	0.123 ± 0.018
NP		–	0.100 ± 0.074	-0.156 ± 0.147	0.387 ± 0.121	0.387 ± 0.112	0.488 ± 0.257

Top-Pair Invariant Mass Distribution:



Where is the top asymmetry in LHC?



- Sensitive variable in this analysis: $|\eta_{top}|-|\eta_{anti\text{-}top}|$

- Define the charge asymmetry as central/de-central asymmetry in $|\eta_{top}|-|\eta_{anti\text{-}top}|$:

$$A_C \coloneqq \frac{N^+ - N^-}{N^+ + N^-}$$

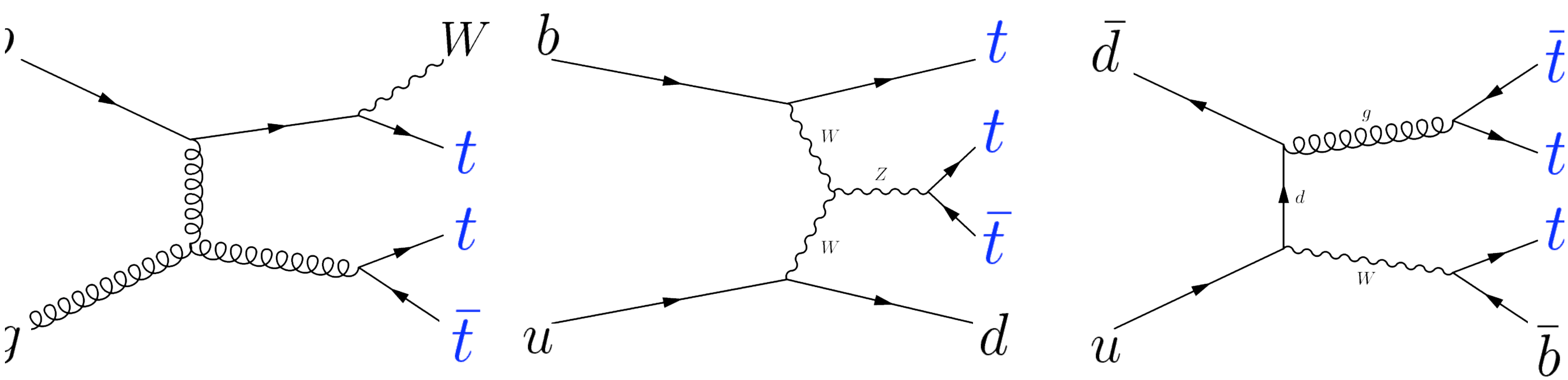
Summary

- W', Z' models are a promising explanation to the CDF top forward-backward asymmetry
- Can be definitively tested at the LHC
  - like-sign top production
  - t+j resonances
  - chiral coupling of W'

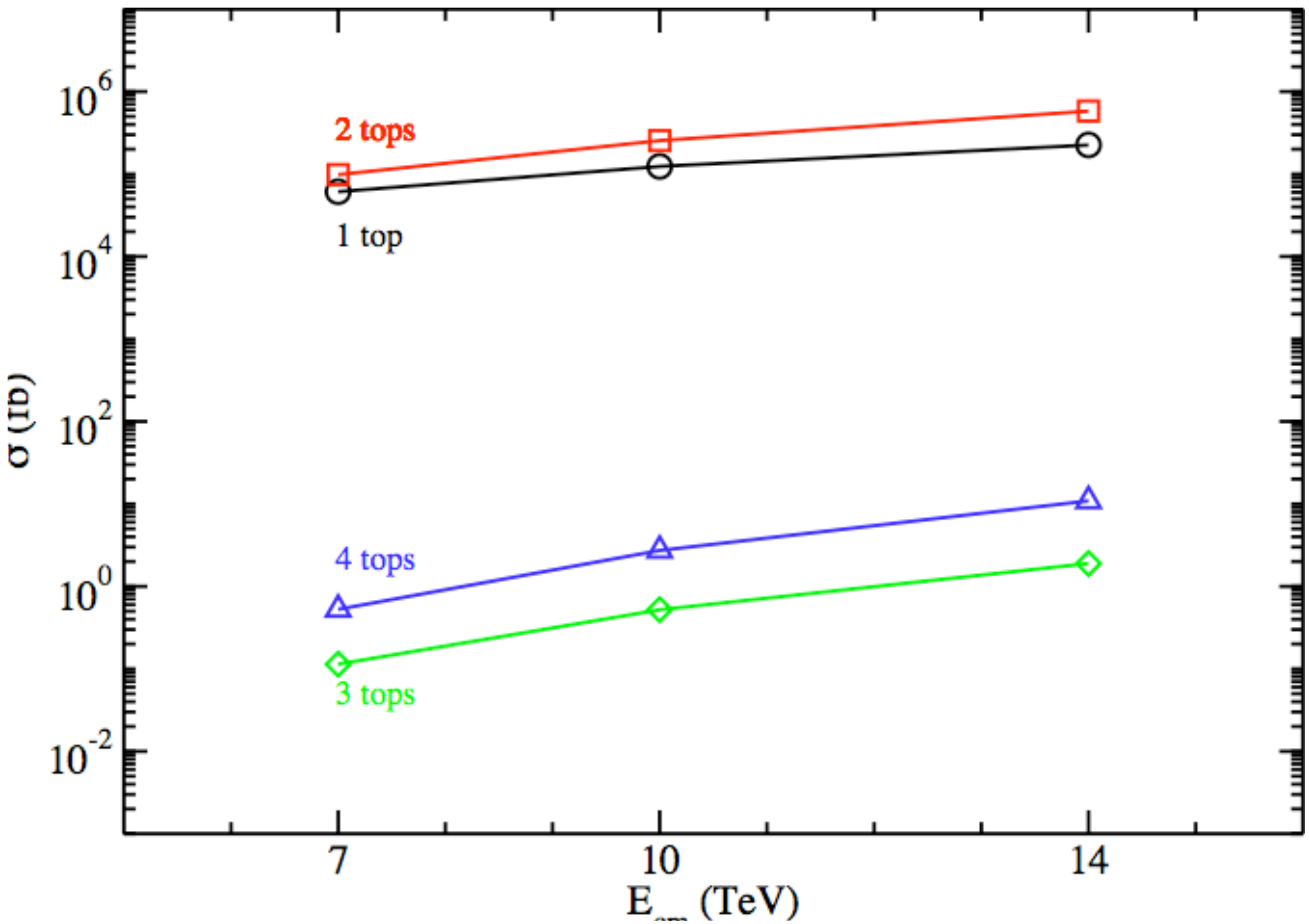
Triple Tops

With V. Barger and B. Yencho, *Phys.Lett. B687 (2010) 70*

- SM production associated with W, b, or single jet (at LO)
- Weak process + initial state b-quark
  - Low rates



Top Production: SM



Small SM triple-top cross-section gets large enhancement in some new physics models

Models: MSSM

- $pp \to \tilde{g}\tilde{g}$ is typically dominant SUSY process at LHC
- "Focus Point" region: (ex: SPS 2)

$$m_{\tilde{g}} < m_{\tilde{q}_i}$$

  - therefore

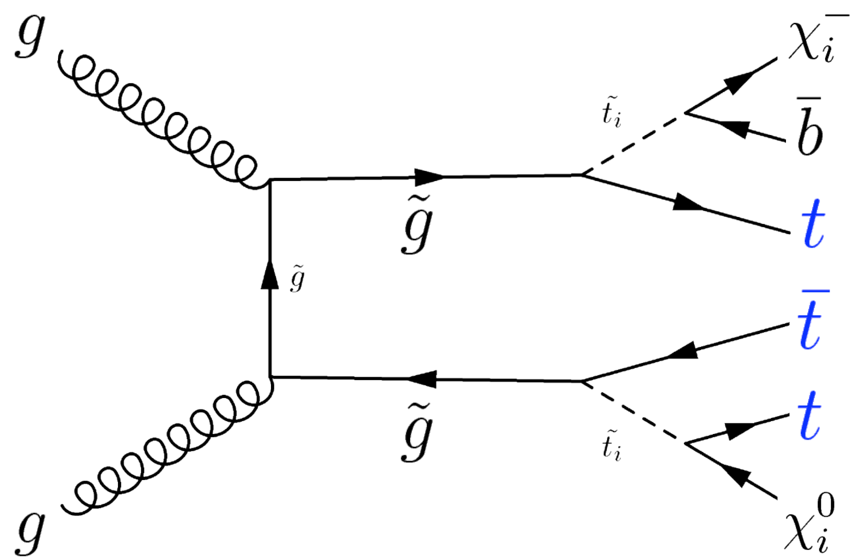
$$\tilde{g} \to q\bar{\tilde{q}}_{L,R},\ \bar{q}\tilde{q}_{L,R}$$ kinematically forbidden

- Can have large BR to tops

$$\begin{aligned} \tilde{g} &\to \chi_i^0 t\bar{t} \\ \tilde{g} &\to \chi_i^{\pm} t\bar{b}\ (\chi_i^{\pm} b\bar{t}) \end{aligned}$$

Models: MSSM

Gluino Branching Fractions	
$\tilde{g} \to 1t + \ldots$	0.21
$\tilde{g} \to t\bar{b}\chi_1^-$	0.080
$\tilde{g} \to \bar{t}b\chi_1^+$	0.080
$\tilde{g} \to t\bar{b}\chi_2^-$	0.024
$\tilde{g} \to \bar{t}b\chi_2^+$	0.024
$\tilde{g} \to 2t + \ldots$	0.11
$\tilde{g} \to t\bar{t}\chi_1^0$	0.099
$\tilde{g} \to t\bar{t}\chi_2^0$	0.012
$\tilde{g} \to t\bar{t}\chi_3^0$	0
$\tilde{g} \to t\bar{t}\chi_4^0$	0



- At SPS 2 (mSUGRA benchmark):

$$m_0 = 1450, \quad m_{1/2} = 300, \quad A_0 = 0, \quad \tan\beta = 10, \quad \mu > 0$$

Models: Z'

- Additional U(1) with interaction term:

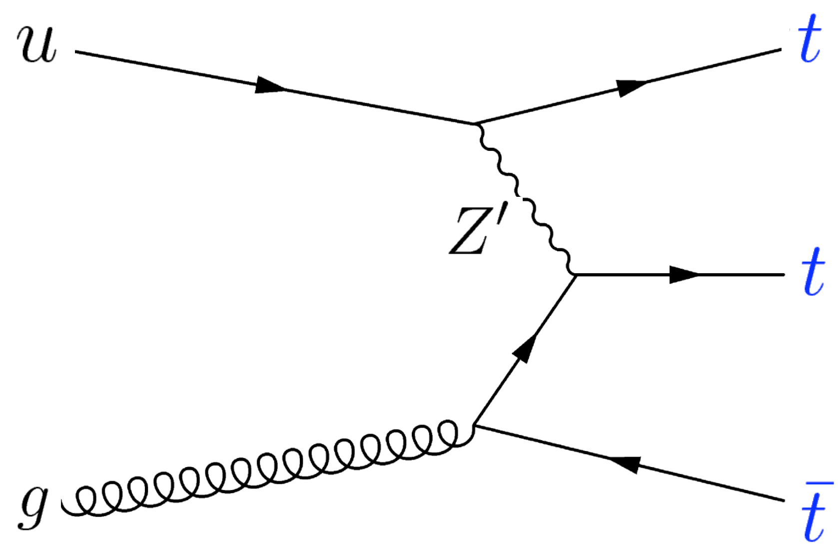
$$\mathscr{L} \supset (g_{\rm X} Z'_\mu \bar{u}\gamma^\mu P_R t + h.c.) + \epsilon_U g_{\rm X} Z'_\mu \bar{u}_i \gamma^\mu P_R u_i$$

- Introduced to explain top-pair FB asymmetry

S. Jung, H. Murayama, A. Pierce, and J.D. Wells, arXiv:0907.4112 [hep-ph]

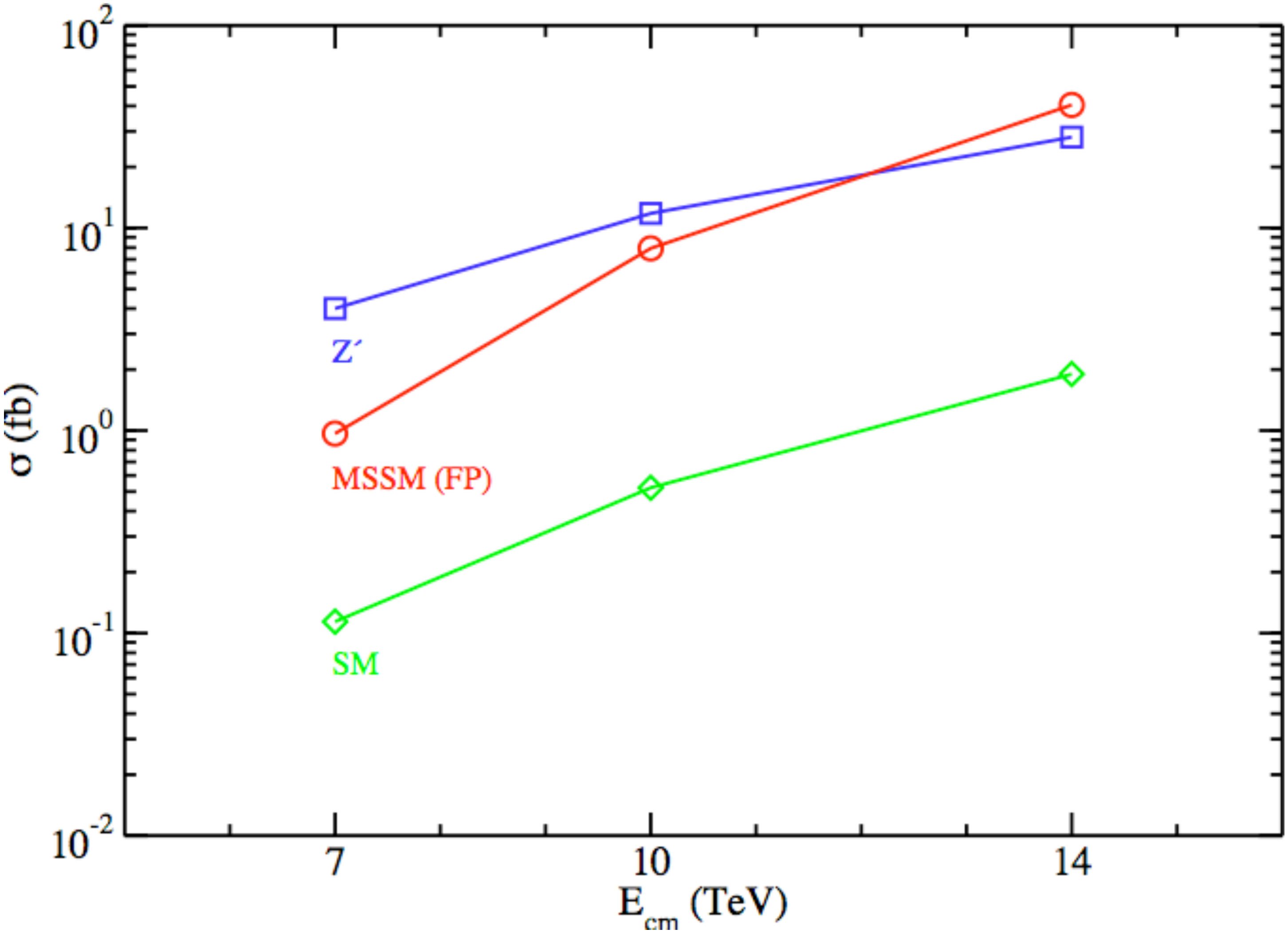
- ϵ_U : forces decay $Z' \to u\bar{u}$
- Best-fit: $M_{z'} = 160 \text{ GeV}, \ \alpha_x = 0.024, \ \epsilon_U < 1$
- We take: $\epsilon_U = 0.1$

Models: Z’

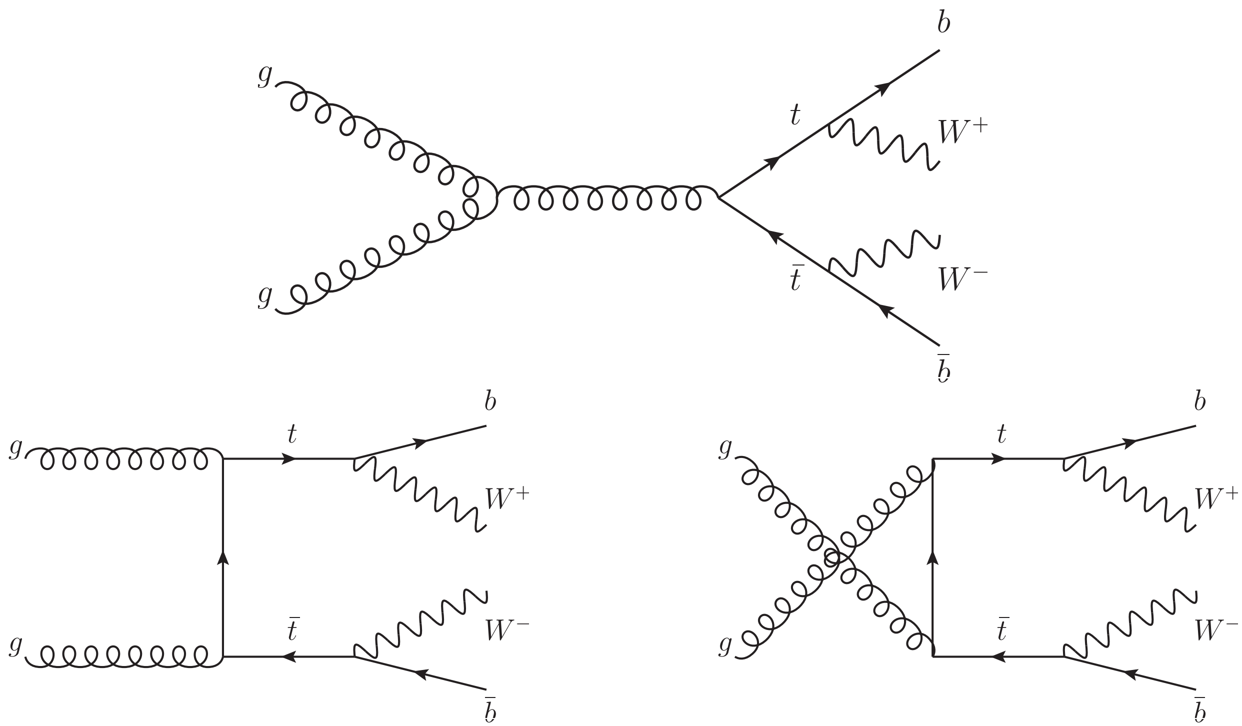


- Leading diagram from t-channel Z’ exchange
- No associated jet, b, or W (at LO)
- Total contribution goes as ϵ_U^2

Triple-Top Cross-Sections



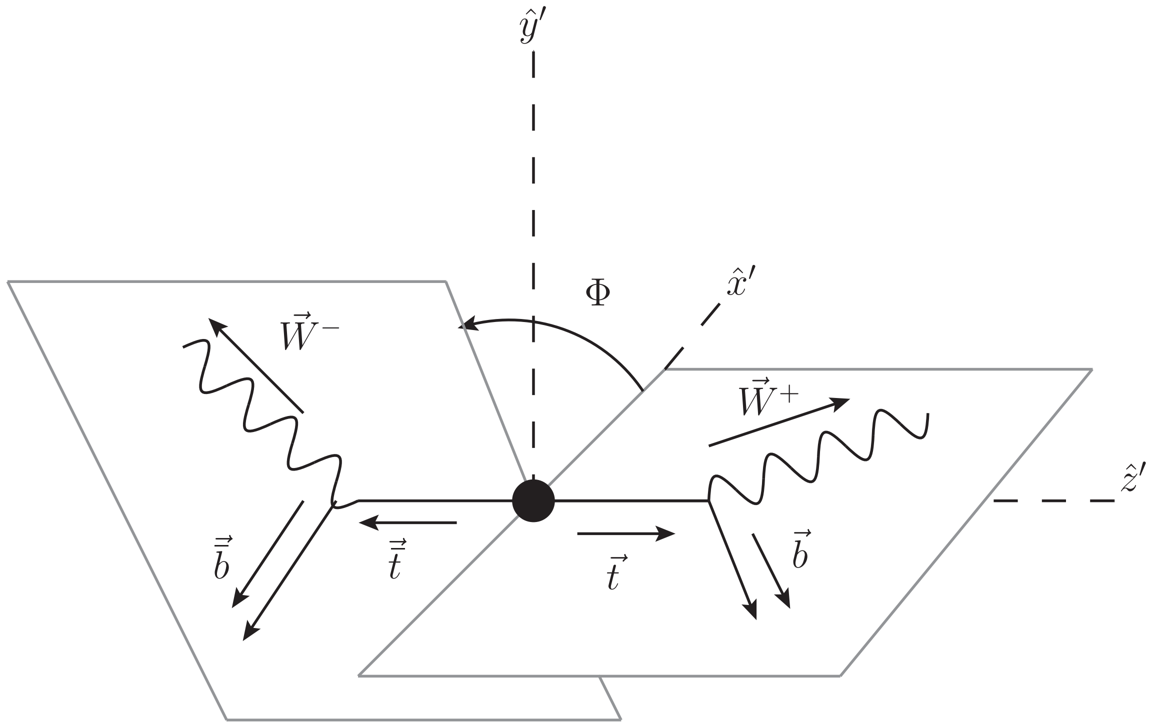
At the LHC, dominant production of $t\bar{t}$ in SM : $gg \to t\bar{t}$



Correlated top quarks spins $\Rightarrow$ angular correlations of their decay products.

We will focus on *azimuthal correlations*.

Define the following coordinate system in c.o.m. of $t\bar{t}$ system:



Φ is the (azimuthal) angle between the t / $\bar{t}$ decay planes about the t momentum axis in $t\bar{t}$ rest frame

- For a given c.o.m. energy $\sqrt{\hat{s}}$:

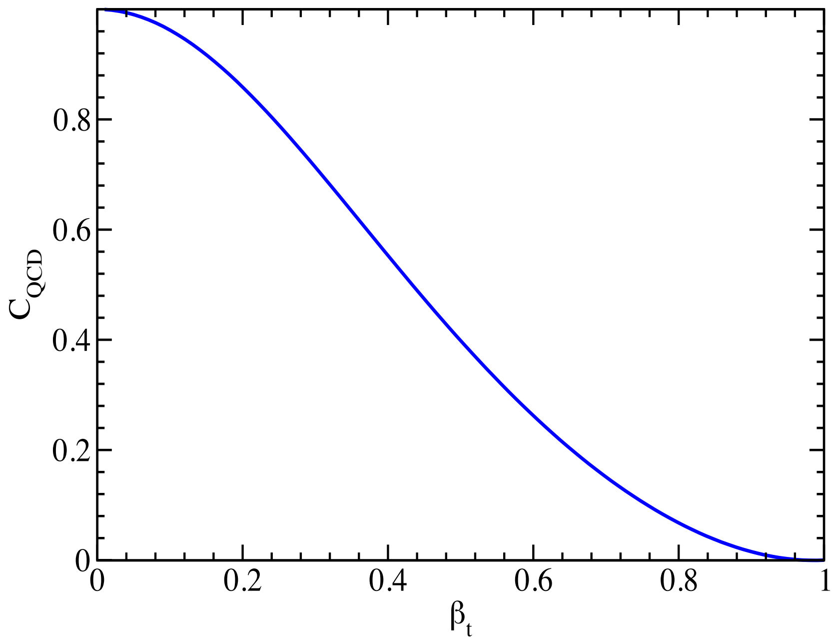
$$\frac{1}{\hat{\sigma}_{\mathrm{QCD}}}\frac{d\hat{\sigma}_{\mathrm{QCD}}}{d\Phi} = \left(\frac{1}{2\pi}\right)\left[1 + C_{\mathrm{QCD}}(\beta_t)\left(\frac{\pi}{4}\right)^2 \frac{(1-2\rho_w)^2}{(1+2\rho_w)^2}\cos(\Phi)\right],$$

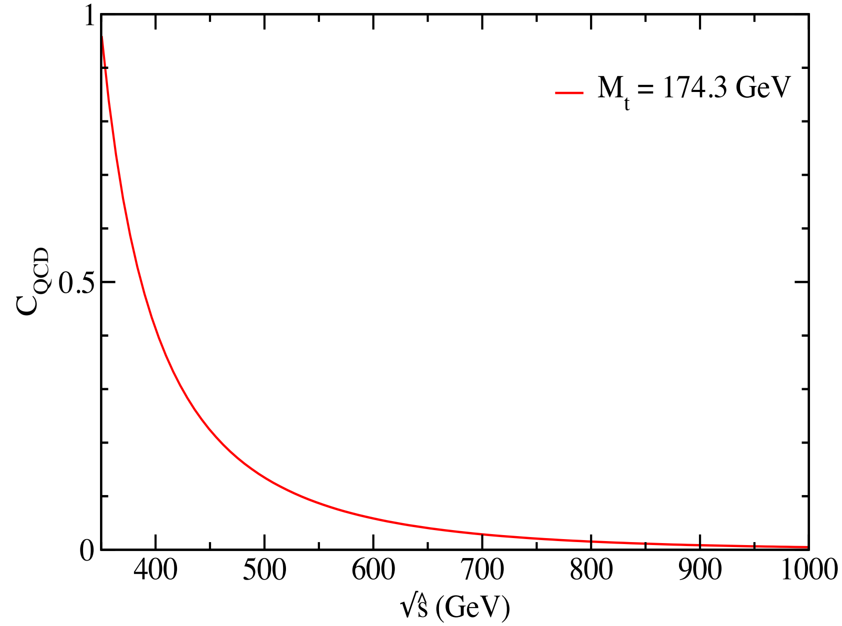
where

$$\rho_W = (m_t^2/M_W^2)$$

$$\beta_t = \sqrt{1-4m_t^2/\hat{s}}$$

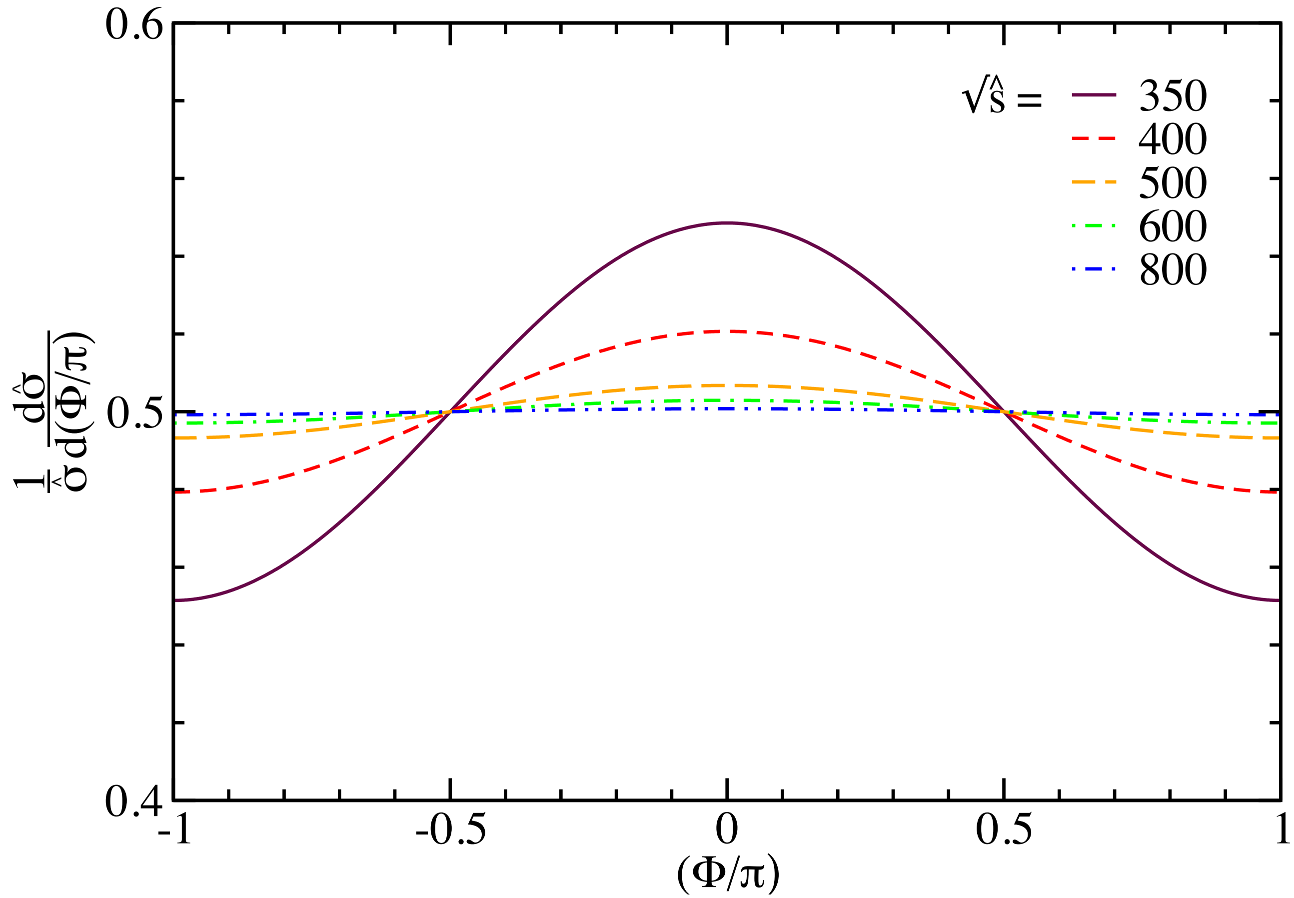
$$C_{\mathrm{QCD}}(\beta_t) = \left(\frac{(1-\beta_t^2)}{\beta_t^2}\right)\left(\frac{\beta_t(33-31\beta_t^2)-(1-\beta_t^2)(33-2\beta_t^2)\tanh^{-1}(\beta_t)}{\beta_t(59-31\beta_t^2)-2(33-18\beta_t^2+\beta_t^4)\tanh^{-1}(\beta_t)}\right)$$





- The function C_{QCD} takes the limits

$$C_{\text{QCD}} \to \begin{cases} 1 \quad \text{as} \quad \beta_t \to 0 \\ 0 \quad \text{as} \quad \beta_t \to 1 \end{cases}$$



low energies $\rightarrow$ *(Potentiallly) Visible correlation*

high energies $\rightarrow$ *flat*

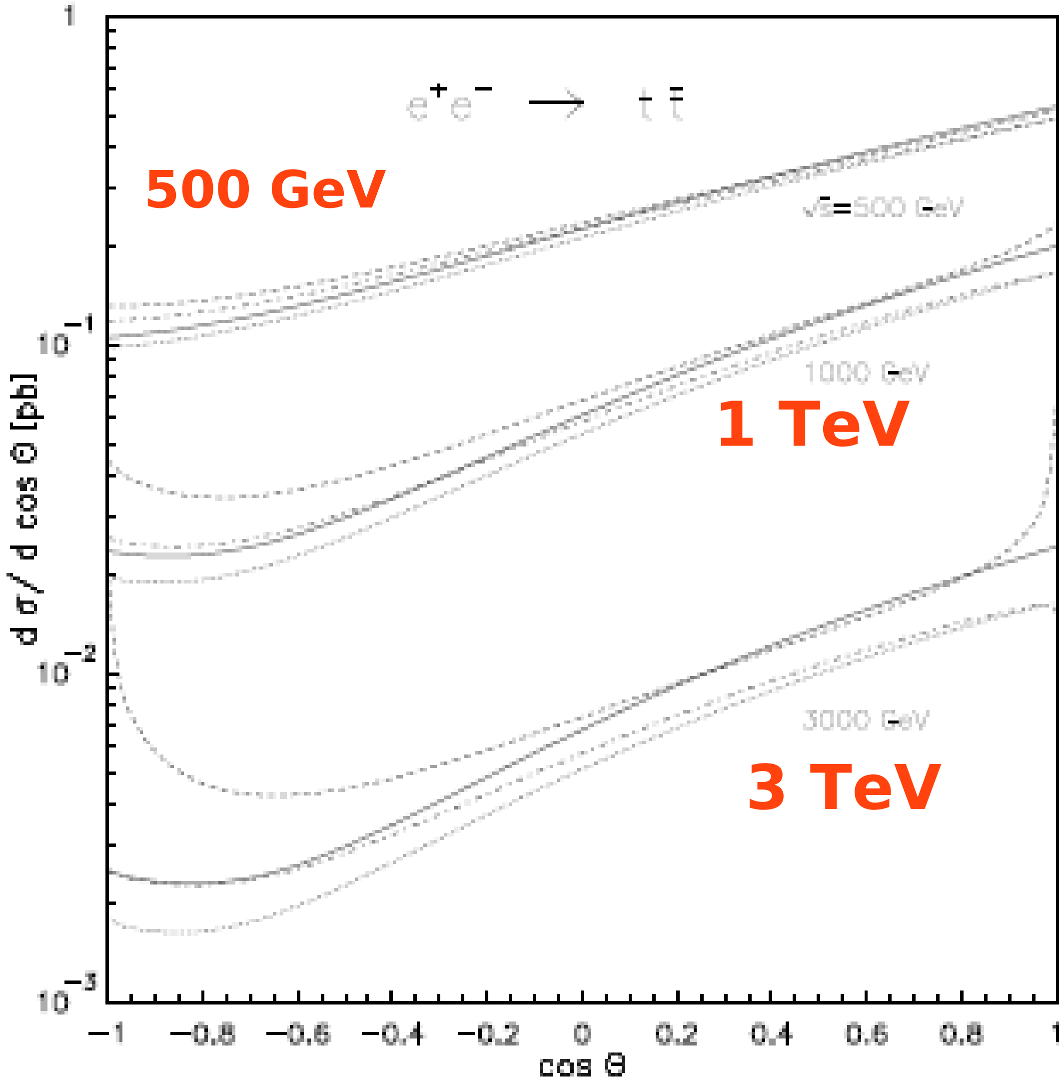
This is the SM prediction at LO.

Top pair in e^+e^-

Precision measurements

of the top mass

of its electroweak coupling

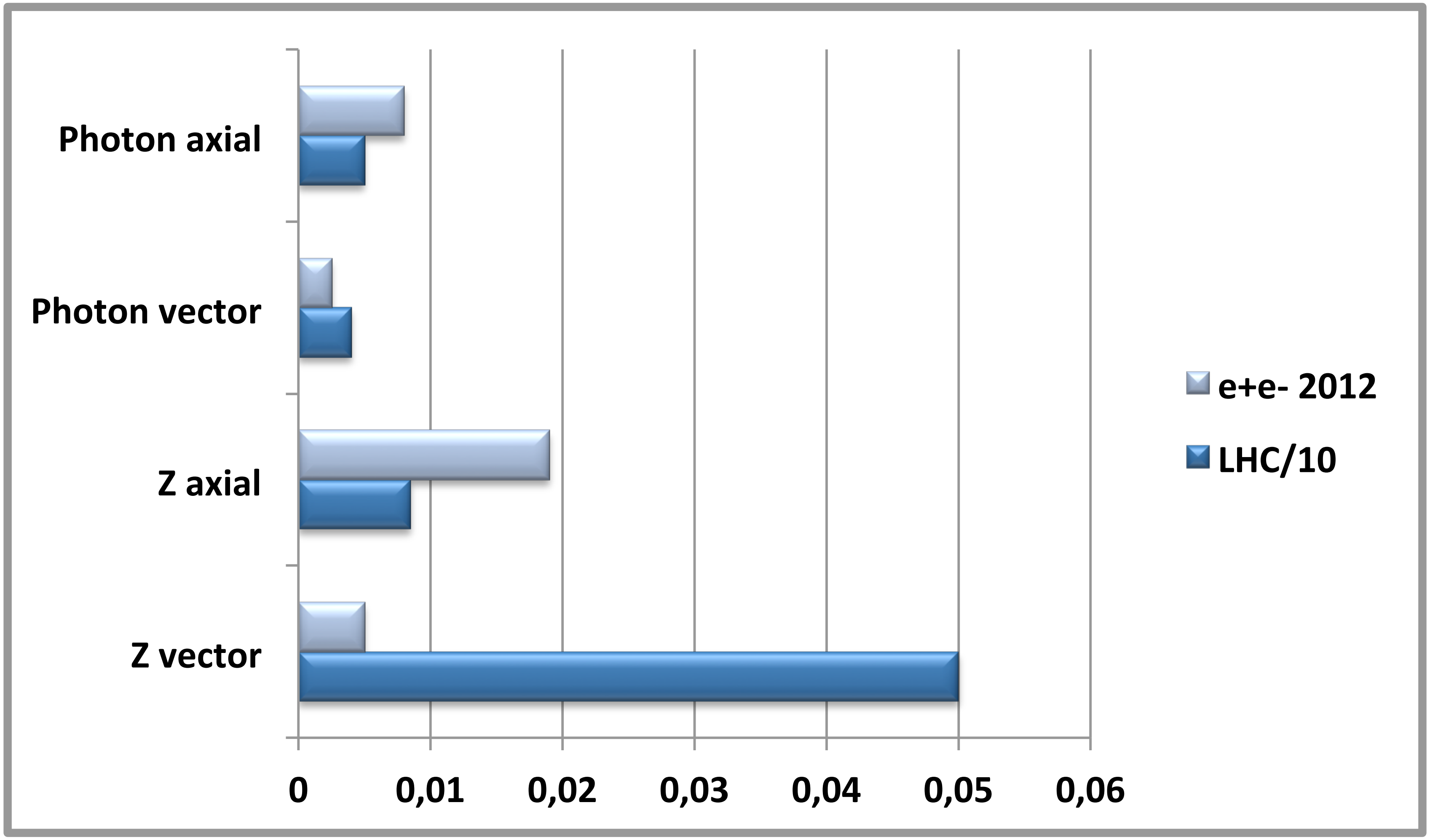


Electroweak corrections

Glover et al. hep/ph04010110

Fleischer et al. hep/ph0302259

Coupling errors for ILC and for LHC.
Note LHC errors are divided by 10



CP violation in top pair production at an e+ e- collider

WYK with Chang and Phillips, Nucl. Phys. B408 (1993) 286.

$$\Gamma^j_\mu = c^j_v \gamma_\mu + c^j_a \gamma_\mu \gamma_5 + c^j_d i \gamma_5 \frac{p_\mu - p'_\mu}{2m_t} + \cdots, \quad j = \gamma, Z.$$

$$M(-+-+) = \quad [c^\gamma_v + r_L c^Z_v - \beta r_L c^Z_a](1+\cos\theta)$$

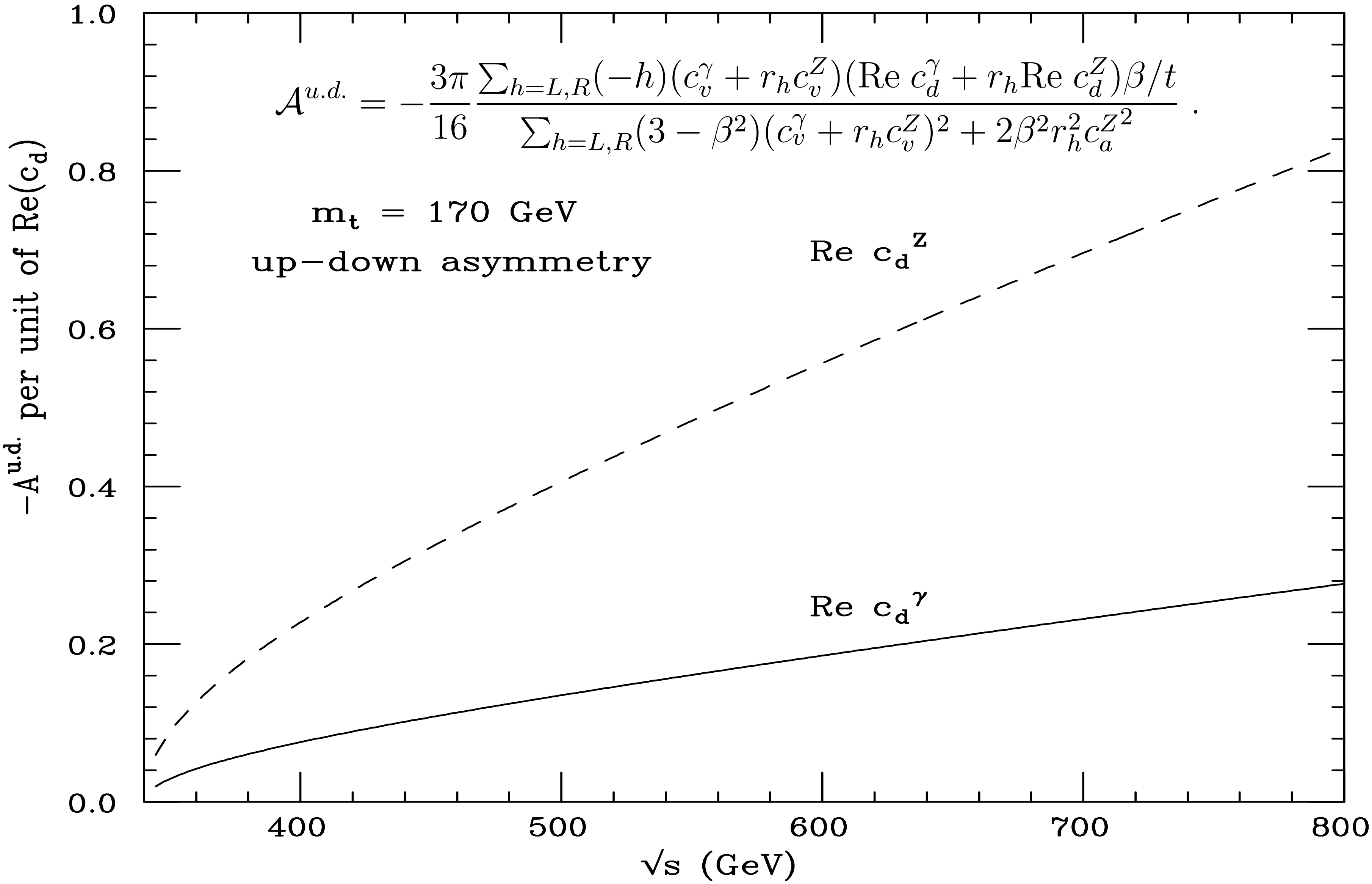
$$M(-++-) = \quad [c^\gamma_v + r_L c^Z_v + \beta r_L c^Z_a](1-\cos\theta)$$

$$M(-+--) = \quad [2t(c^\gamma_v + r_L c^Z_v) - \tfrac{i}{2}(c^\gamma_d + r_L c^Z_d)\beta/t]\sin\theta$$

$$M(-+++) = \quad [2t(c^\gamma_v + r_L c^Z_v) + \tfrac{i}{2}(c^\gamma_d + r_L c^Z_d)\beta/t]\sin\theta \ .$$

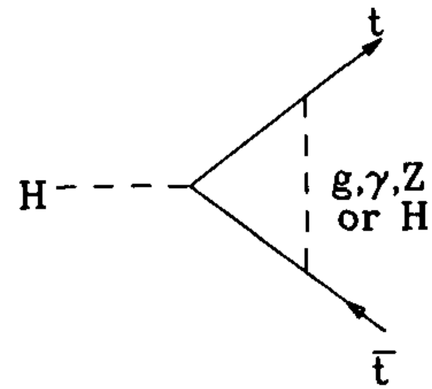
$t = m_t/\sqrt{s}, \ z = m_Z/\sqrt{s}, \ \beta^2 = 1 - 4t^2 \qquad r_L = (\frac{1}{2} - x_W)/[(1-z^2)\sqrt{x_W(1-x_W)}]$

$$\mathcal{A}^{u.d.}(\theta) = \frac{[dN(\ell^+,\mathrm{up}) + dN(\ell^-,\mathrm{up})] - [dN(\ell^+,\mathrm{down}) + dN(\ell^-,\mathrm{down})]}{[dN(\ell^+,\mathrm{up}) + dN(\ell^-,\mathrm{up})] + [dN(\ell^+,\mathrm{down}) + dN(\ell^-,\mathrm{down})]} .$$



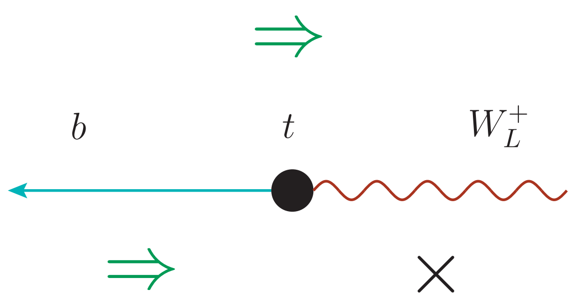
CP violation in the decay of neutral Higgs boson into top pair and W pair, with D. Chang, *Phys.Lett. B305 (1993) 261.*

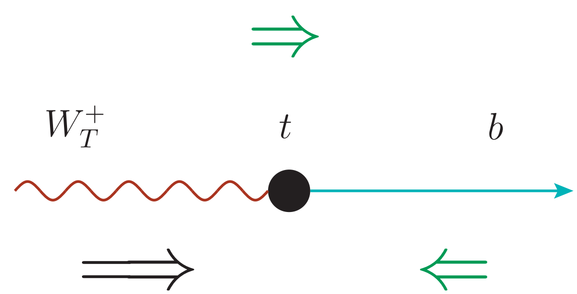
$$\mathcal{L}_{H\bar{t}t} = -(m_t/v)\bar{t}(AP_L + A^* P_R)tH$$



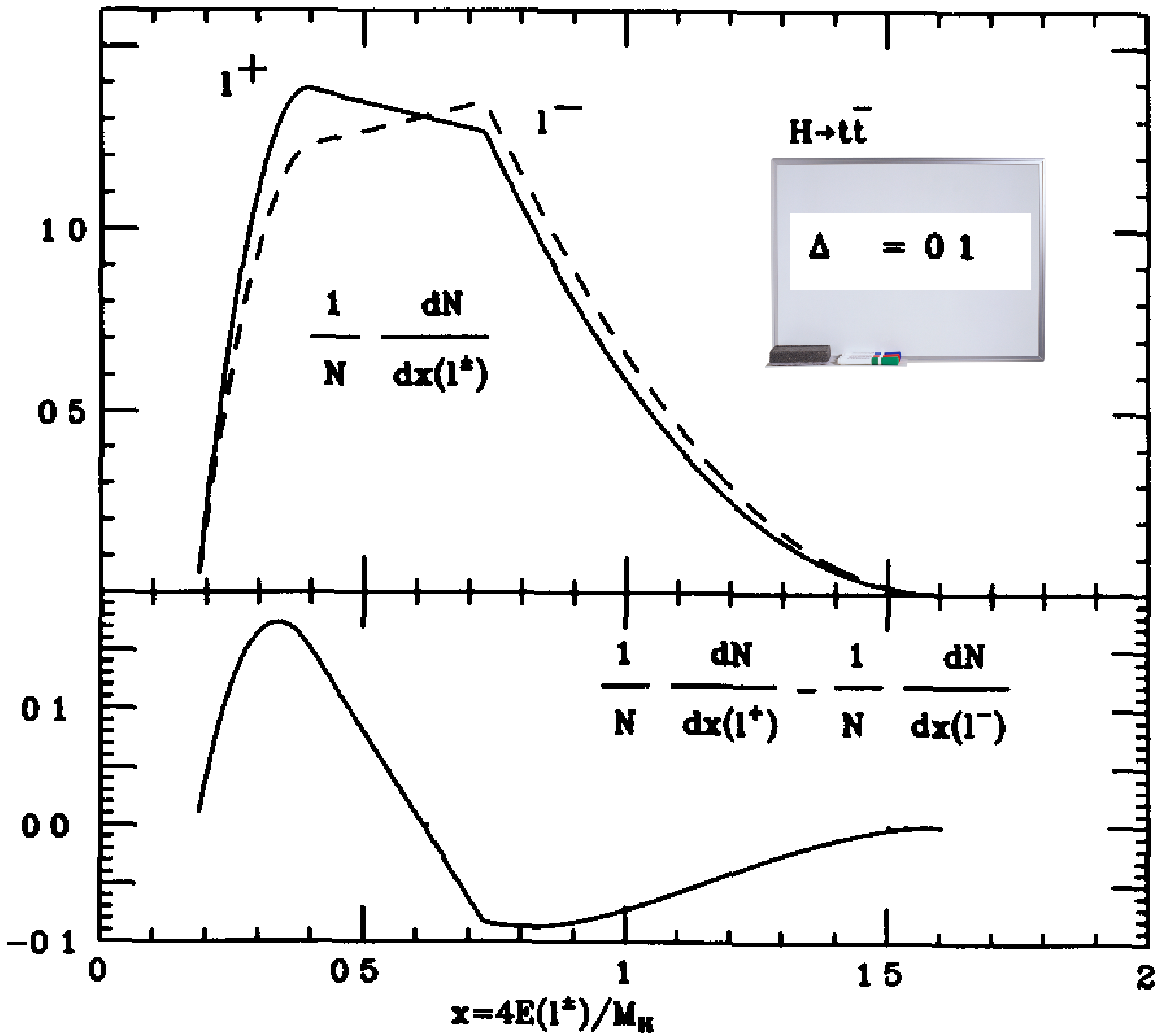
$$\Delta \equiv \frac{N(t_L\bar{t}_L) - N(t_R\bar{t}_R)}{N(\text{all } t\bar{t} \text{ from } H)} = \frac{\delta^{\rm QCD} + \delta^{\gamma} + \delta^{Z} + \delta^{H} + \delta^{WW} + \delta^{ZZ}}{\beta_t^2 A_R^2 + A_I^2}$$

$$\delta^{\rm QCD} = (C\alpha_S/2)\mathrm{Im}(A^2)(1-\beta_t^2)$$





Longitudinal $\sim$ 70% Transverse $\sim$ 30%



l^+
l^-
$H \to t\bar{t}$
$\Delta = 0\ 1$
$\frac{1}{N}\frac{dN}{dx(l^\pm)}$
$\frac{1}{N}\frac{dN}{dx(l^+)} - \frac{1}{N}\frac{dN}{dx(l^-)}$
1 0
0 5
0 1
0 0
−0 1
0
0 5
1
1 5
2
$x=4E(l^\pm)/M_H$

Conclusion

- Rich physics in the top sector
- Decoding angular distributions
- Possible CP hiding place

CMS uses a kinematic likelihood technique to reconstruct top pairs in 4.7 fb^{-1} of l+jets data at 7 TeV finding $A_C = 0.004 \pm 0.010(\mathrm{stat}) \pm 0.012(\mathrm{sys})$ [8]. They use a weighting technique to solve for the $t\bar{t}$ kinematics in 5.0 fb^{-1} of dilepton data to find $A_C = 0.050 \pm 0.043(\mathrm{stat})^{+0.010}_{-0.039}(\mathrm{sys})$ [9]. In the same dilepton sample, the charge asymmetry based on lepton rapidities is measured to be $A_C = 0.010 \pm 0.015 \pm 0.006$.

ATLAS has examined 1.04 fb^{-1} of l+jets top events at 7 TeV using a kinematic likelihood reconstruction to find $A_C = -0.018 \pm 0.028(\mathrm{stat}) \pm 0.023(\mathrm{sys})$ [10]. ATLAS has also examined the asymmetry in 4.7 fb^{-1} of dilepton data [11], using a matrix element method for the top reconstruction, where they find $A_C = 0.057 \pm 0.024(\mathrm{stat}) \pm 0.015(\mathrm{sys})$. Combining l+jets and dilepton results, ATLAS finds a best top charge asymmetry of $A_C = 0.029 \pm 0.018(\mathrm{stat}) \pm 0.014(\mathrm{sys})$.